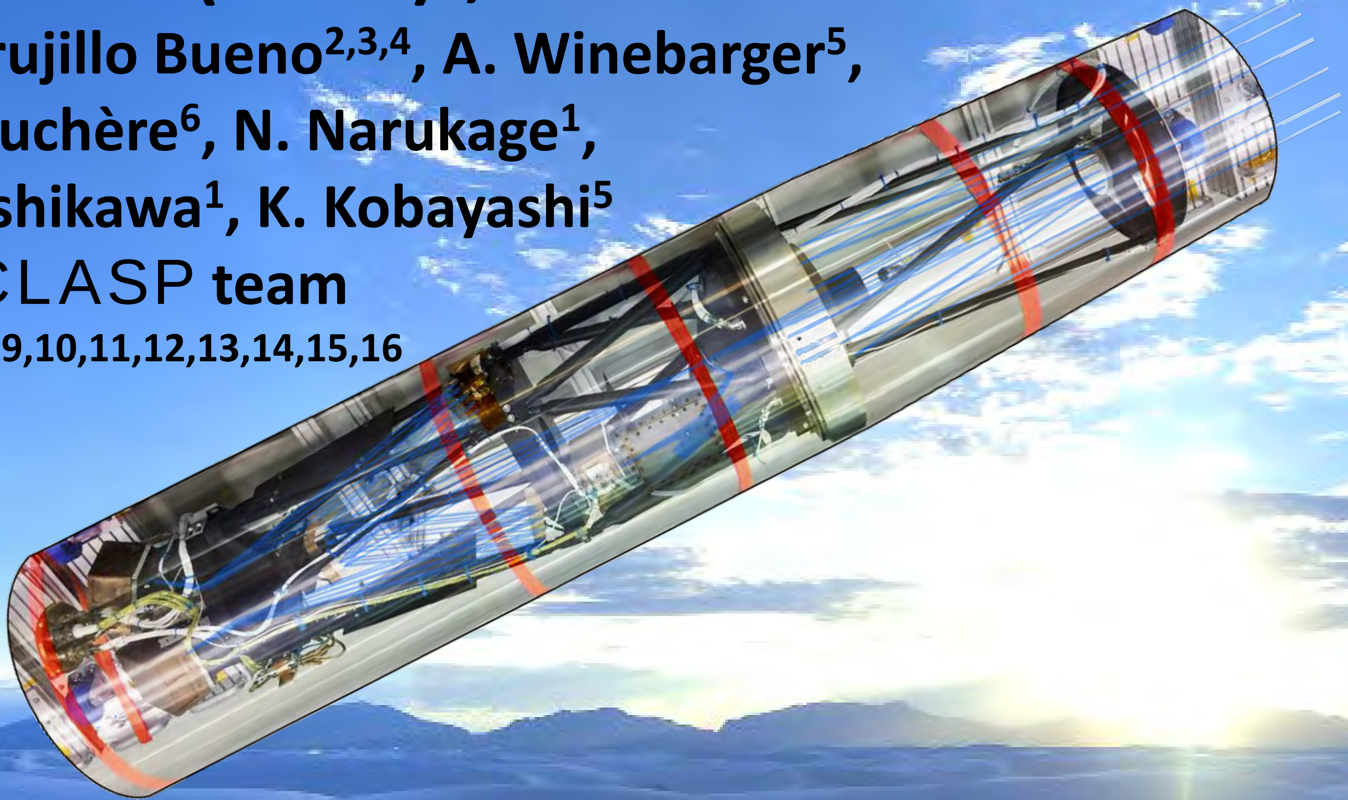
Lyman-α scattering polarization observed with the Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP)

R. Kano (NAOJ)[1],

J. Trujillo Bueno[2,3,4], A. Winebarger[5], F. Auchère[6], N. Narukage[1], R. Ishikawa[1], K. Kobayashi[5] & CLASP team

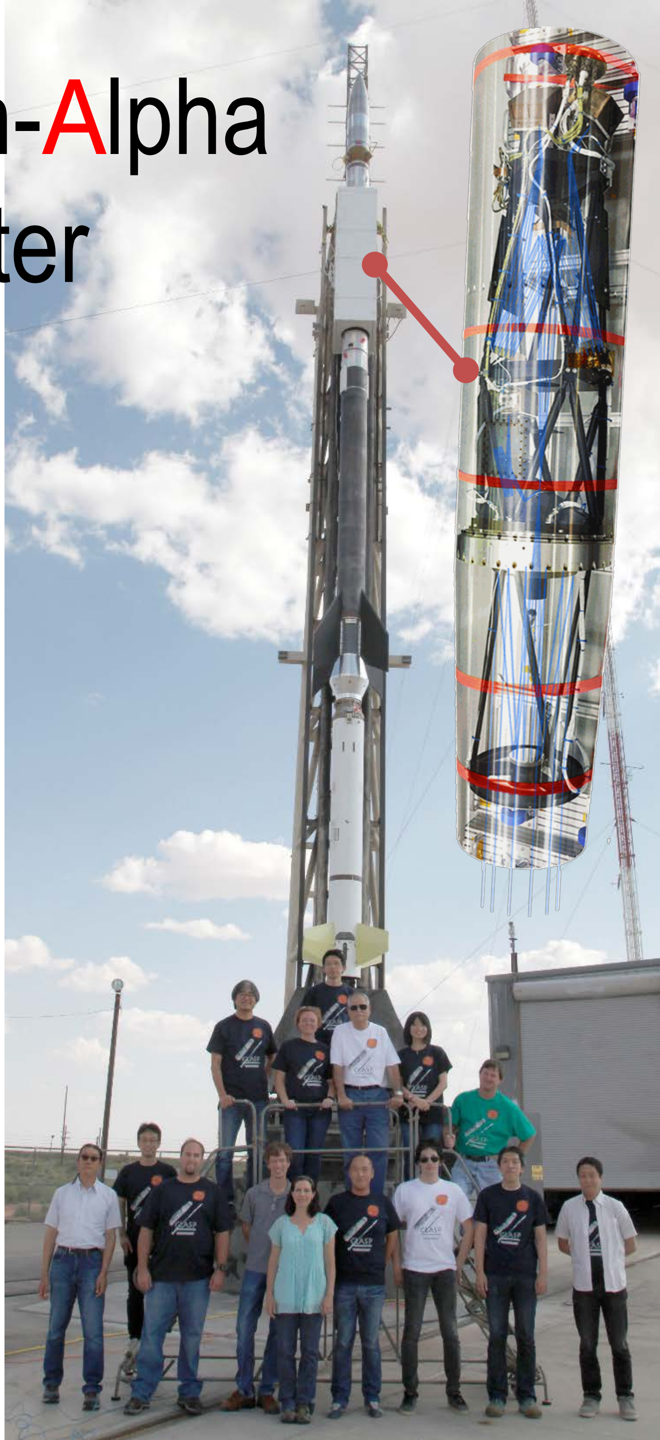
6,7,8,9,10,11,12,13,14,15,16



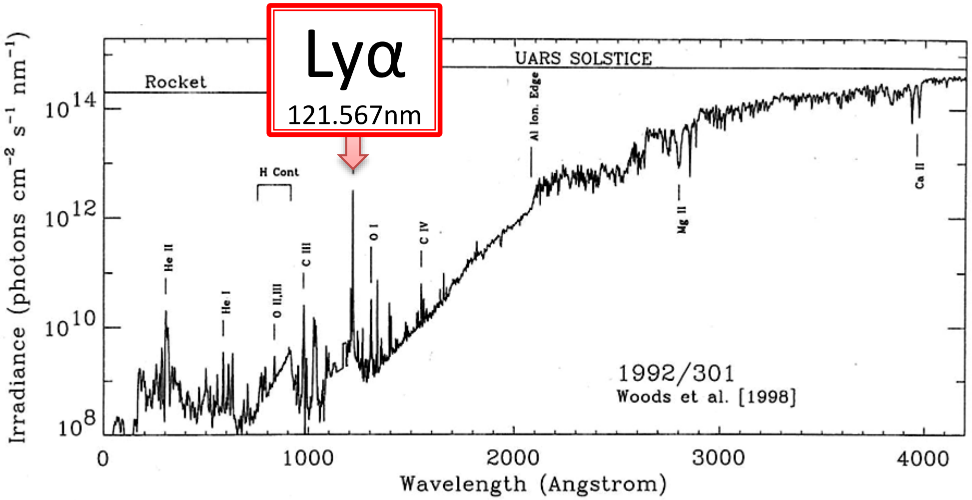
1 NAOJ, 2 IAC, 3 ULL, 4 CSIC, 5 NASA/MSFC, 6 IAS, 7 ISAS/JAXA, 8 SOKENDAI, 9 Kyoto Univ, 10 NIFS, 11 IRSOL, 12 ASCR, 13 MPS, 14 LMSAL, 15 HAO, 16 Univ. of Oslo

Chromospheric Lyman-Alpha Spectro-Polarimeter

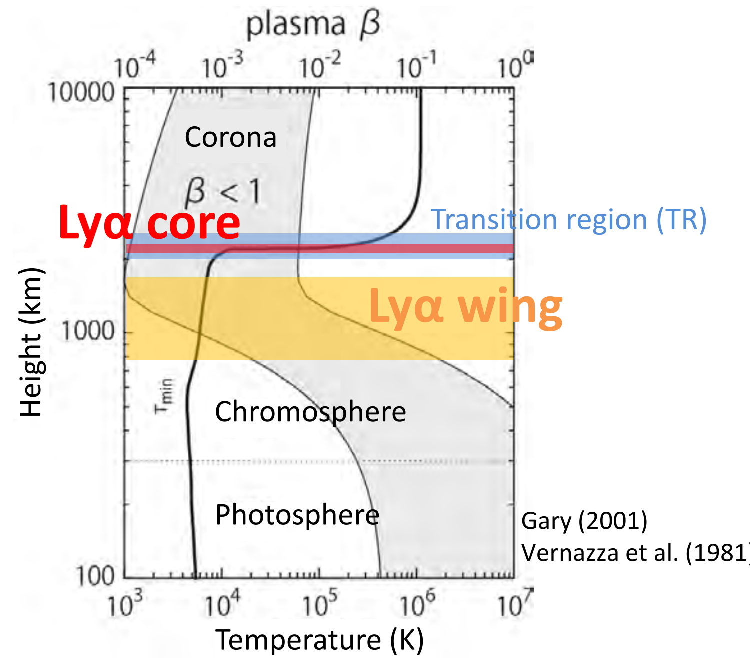
- **High-precision** (<0.1%) **spectro-polarimetry** in **VUV**.
- **First detection** of scattering polarization in the **Lyα line** (121.6 nm).
- **Exploration** of **magnetic fields** in **the upper chromosphere** and **the transition region** via the Hanle effect.



Why Lyα line?



Solar spectrum in VUV range



Plasma-β and formation height of Lyα in the solar atmosphere

- Brightest line in VUV chromospheric emission lines, and bright even in quiet Sun as well as active regions.
- Line core is emitted by the plasma located between upper chromosphere and **transition region (TR)**.
- Good sensitivity to magnetic field of 10 – 100 G via Hanle effect.

➔ Lyα line is a suitable candidate to constrain magnetic fields and the geometrical complexity of the low-β TR plasma over the entire solar disk.

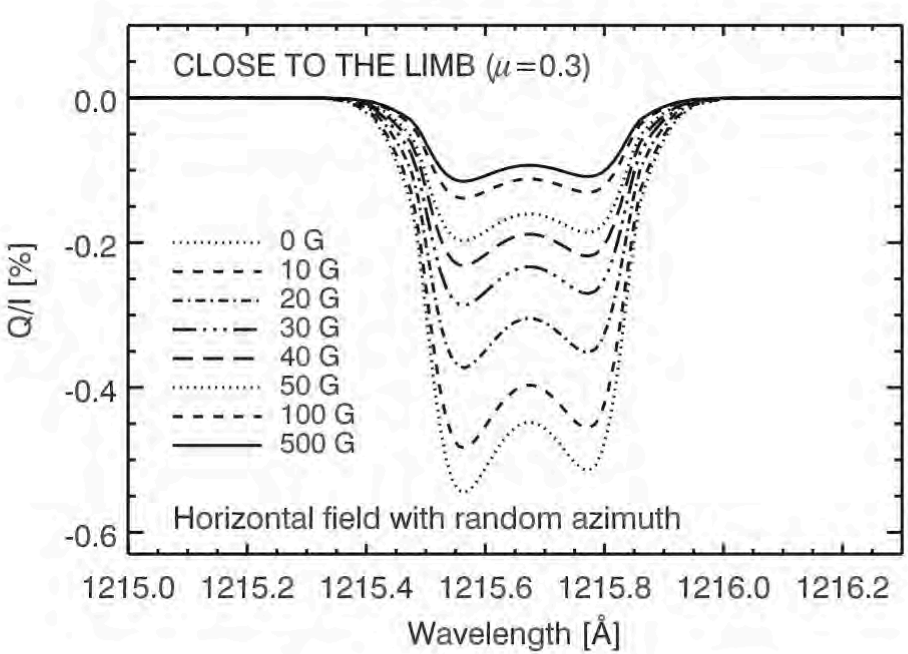
Polarization in Lyα line

Line core:

- **Scattering polarization** + **Hanle effect**
- sensitive to 10 - 100 G

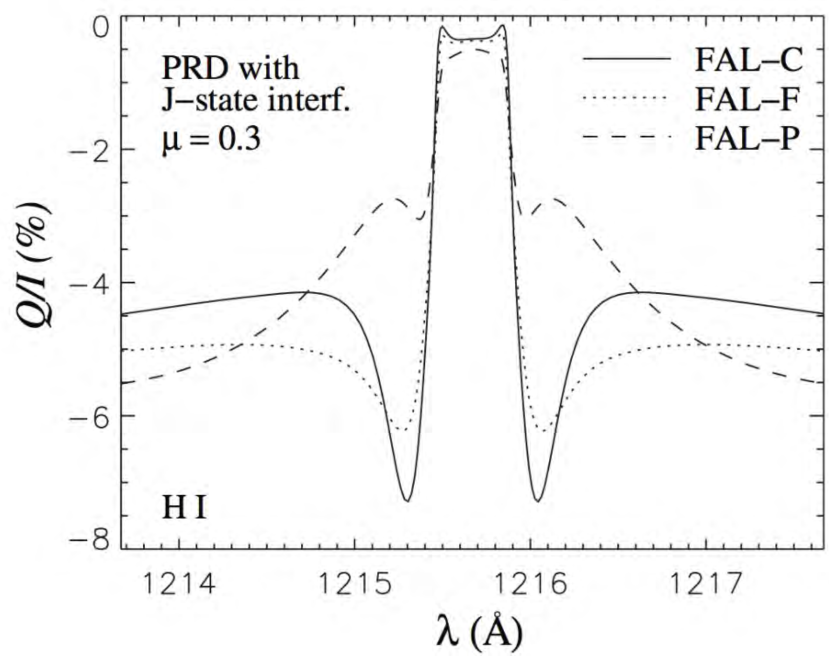
Line wing:

- **Scattering polarization**
- sensitive to temperature structure



in SI

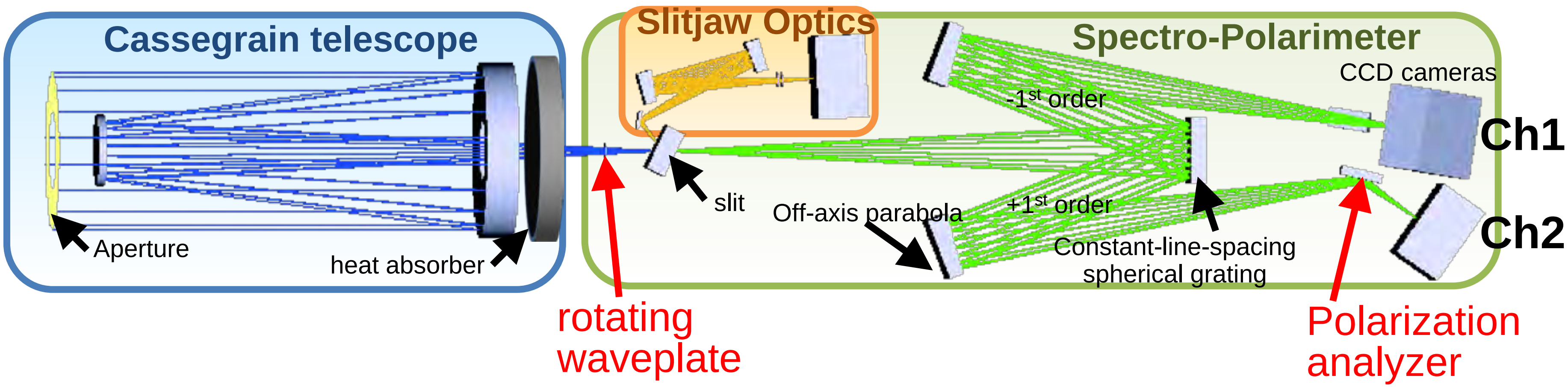
Trujillo Bueno et al. (2011)



Belluzzi et al. (2012)

CLASP Instrument

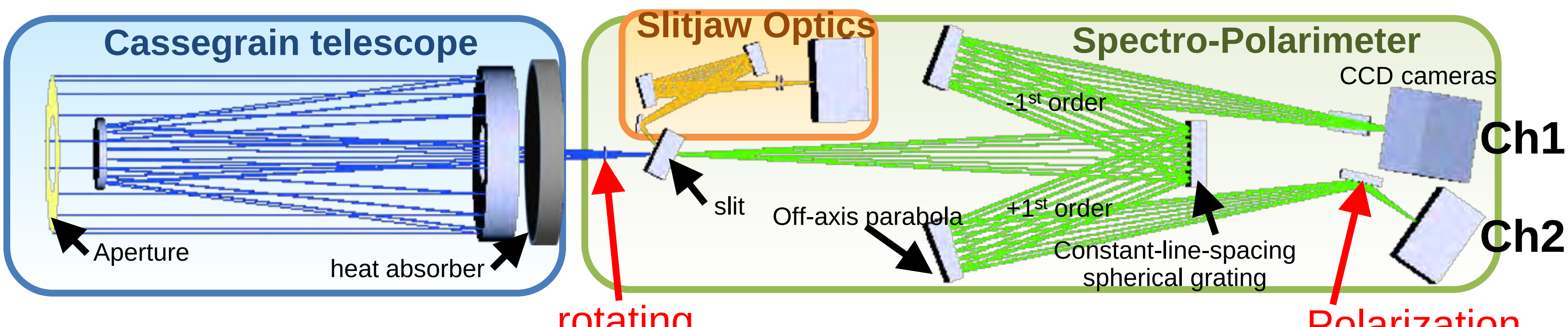
Narukage et al. (2015, Applied Optics)



- Two symmetric channels: **Ch1 & Ch2**
  - Simultaneously measure **orthogonal polarization** states
- Realize high throughput in VUV
  - Minimize the number of optical components
  - Apply high-reflectivity coating to all optical components

CLASP Instrument

Narukage et al. (2015, Applied Optics)



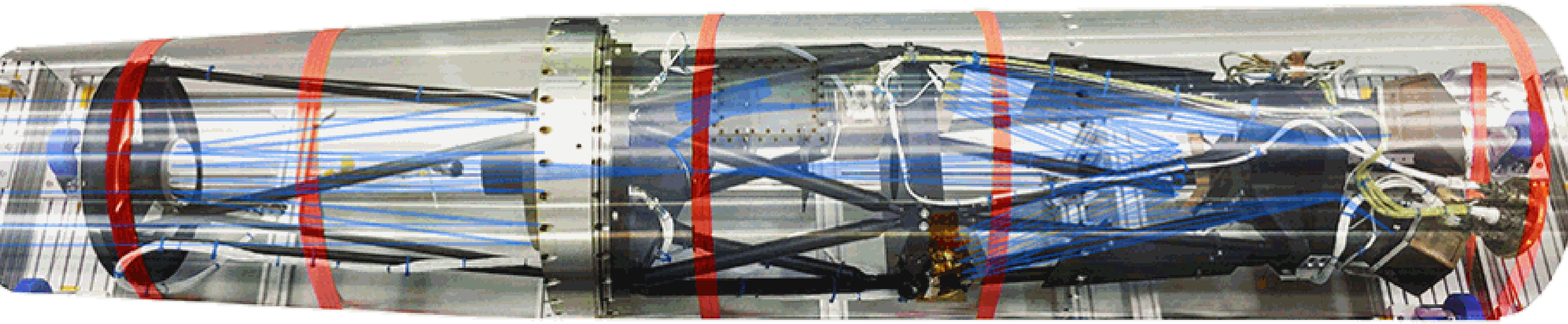
Cassegrain Telescope	
Aperture	ϕ270.0 mm
Focal Length	2614 mm (F/9.68)
Visible light rejection	“Cold Mirror” coating on primary mirror

Slitjaw Optics	
Wavelength	121.567 nm (NB filter)
Plate scale	**1.03’’/pixel**
FoV	527’’ × 527’’

Spectro-Polarimeter		
Optics	Inverse Wadsworth mounting	
Wavelength	121.567 ± 0.61 nm	
Slit	1.45’’ (width), 400’’ (length)	
Grating	Spherical constant-line-spacing, 3000/mm	
CCD camera	512 × 512 pixel	13μm/pixel
Plate scale	0.0048 nm/pixel	**1.11’’/pixel**
Resolution	**0.01nm**	3’’
Sensitivity	**0.1%**	

CLASP Instrument

Narukage et al. (2015, Applied Optics)



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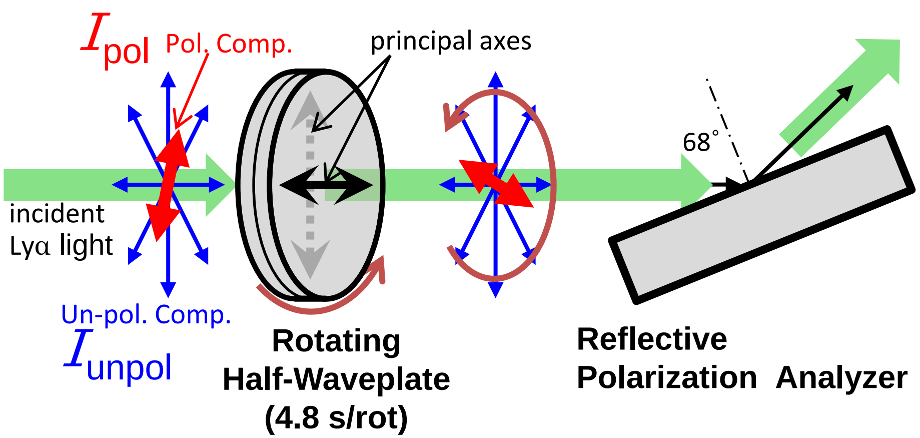
Sensitivity	**0.1%**	

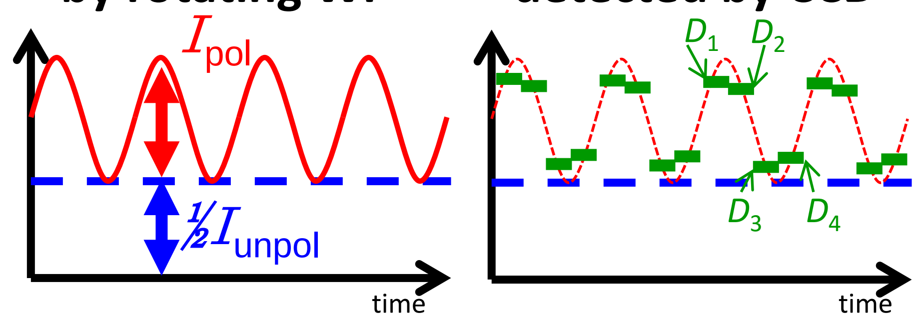
Modulation & Demodulation

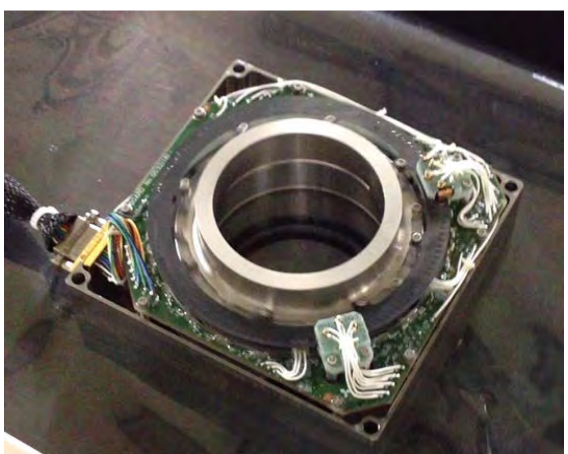
- CLASP is optimized for linear polarization, because *V/I* due to Zeeman is expected to be too small (~0.005% @10G in the Lyman-α by Zeeman effect).

CLASP Polarimeter



Modulation





Demodulation

from CCD exposures

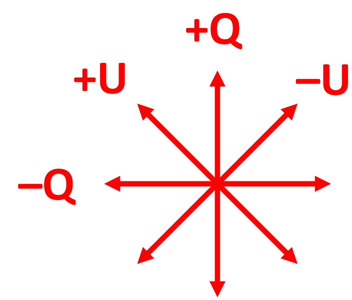
a: modulation coefficient

K: throughput value

$$Q = aK\{(D_1 - D_2 - D_3 + D_4) + \dots\}$$

$$U = aK\{(D_2 - D_3 - D_4 + D_5) + \dots\}$$

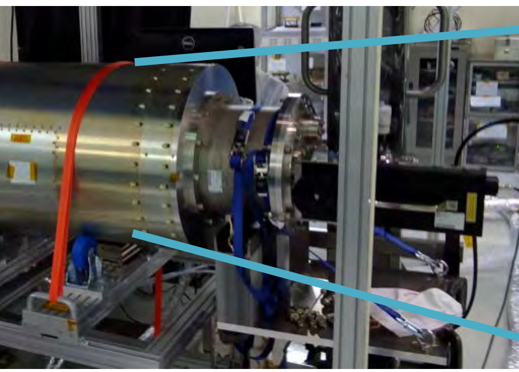
$$I = K\{(D_1 + D_2 + D_3 + D_4) + \dots\}$$

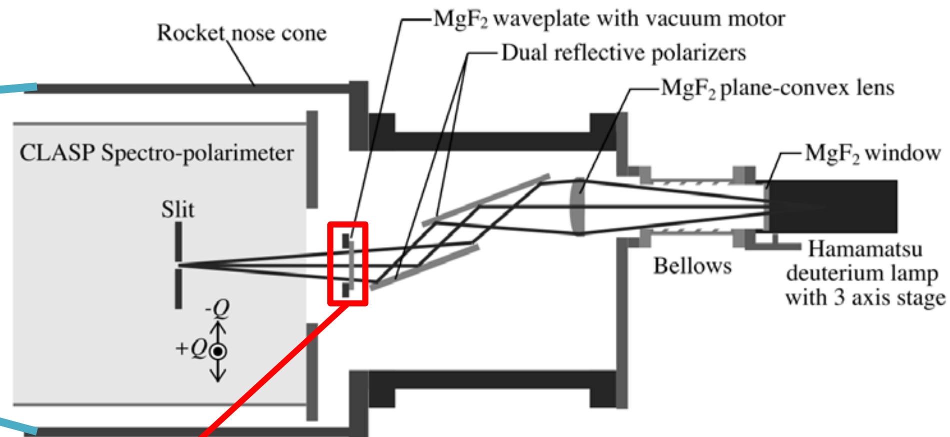


Giono (2016, PhD) & Giono et al. (2016, SP)

SP polarization calibration

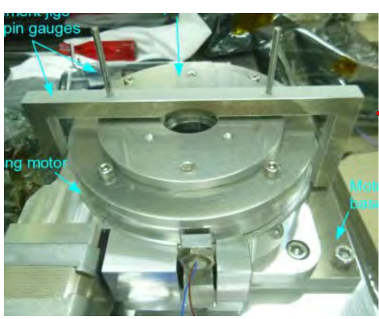
We performed the polarization calibration only to SP,
because the instrument polarization in the telescope is negligibly small.



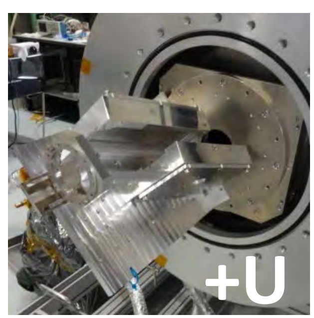


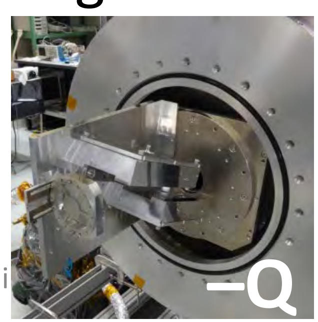
2 ways to change the orientation of the incident linear polarization

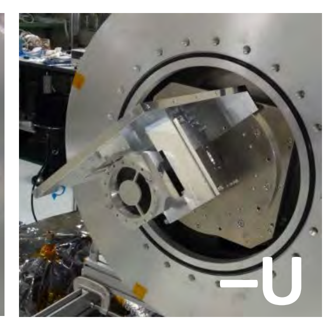
- Rotate ½ waveplate

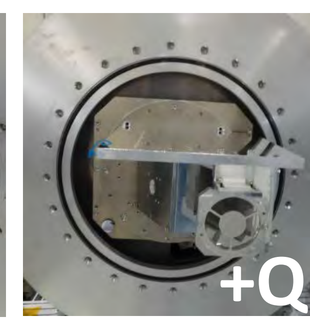


- Rotate entire light source

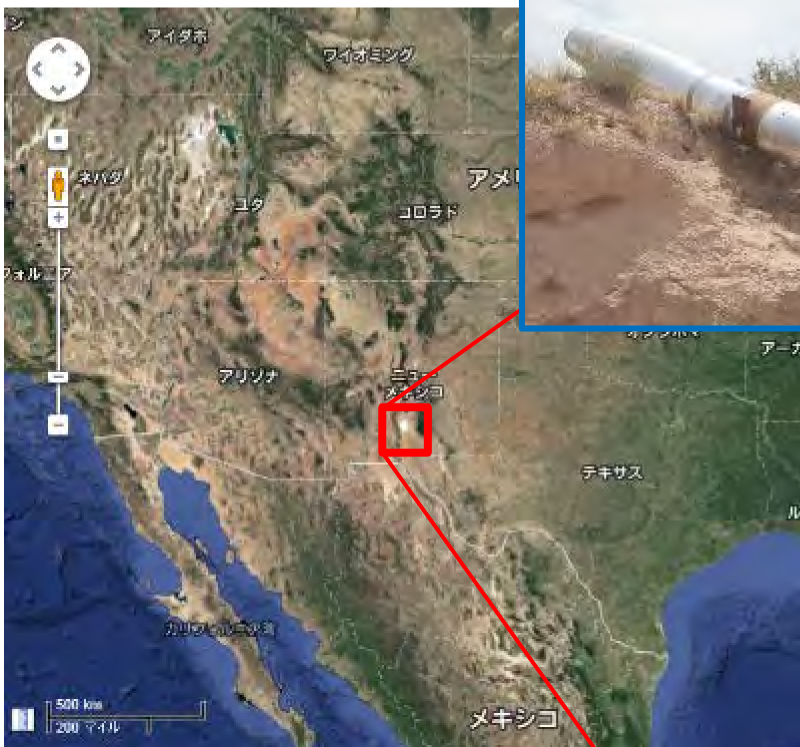








CLASP was launched on Sep.3, 2015 in White Sands.



Ballistic flight:

- max height: 261km.
- ~300s in space (>150km).
- returned safely.

Observing procedure

Peak height was ~ 261 km.

[1] Initial ~ 16 sec

Disk center for the on-flight polarization calibration.

– SJ: >16 images with 0.6s cad.

– SP: >33 images with 0.3s cad.

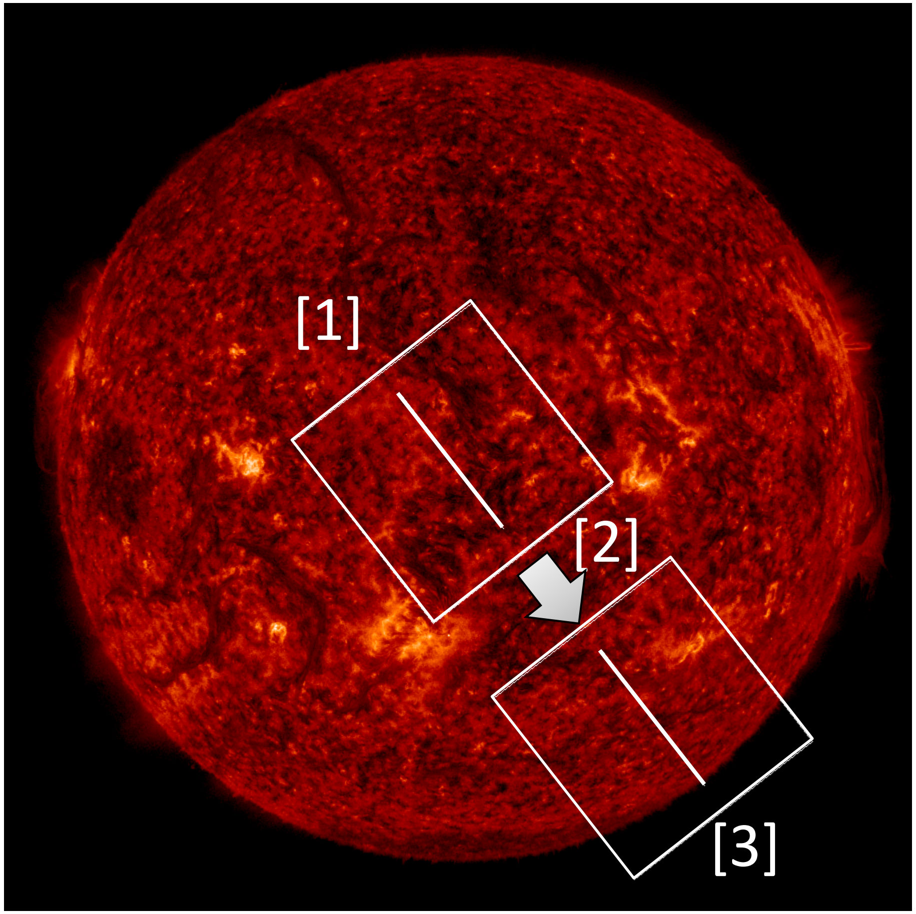
[2] ~ 30 sec for repointing.

[3] Remaining ~ 289 sec

Sit & stare in QS near SW limb. Slit is perpendicular to the limb.

– SJ: > 466 images with 0.6 cad.

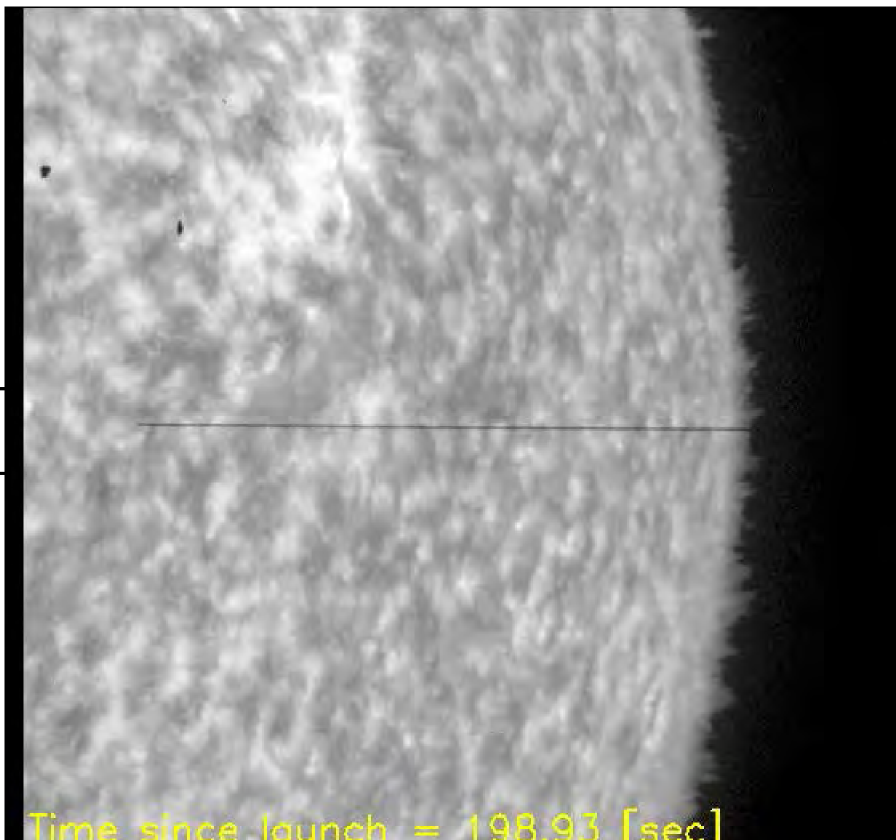
– SP: > 933 images with 0.3s cad.

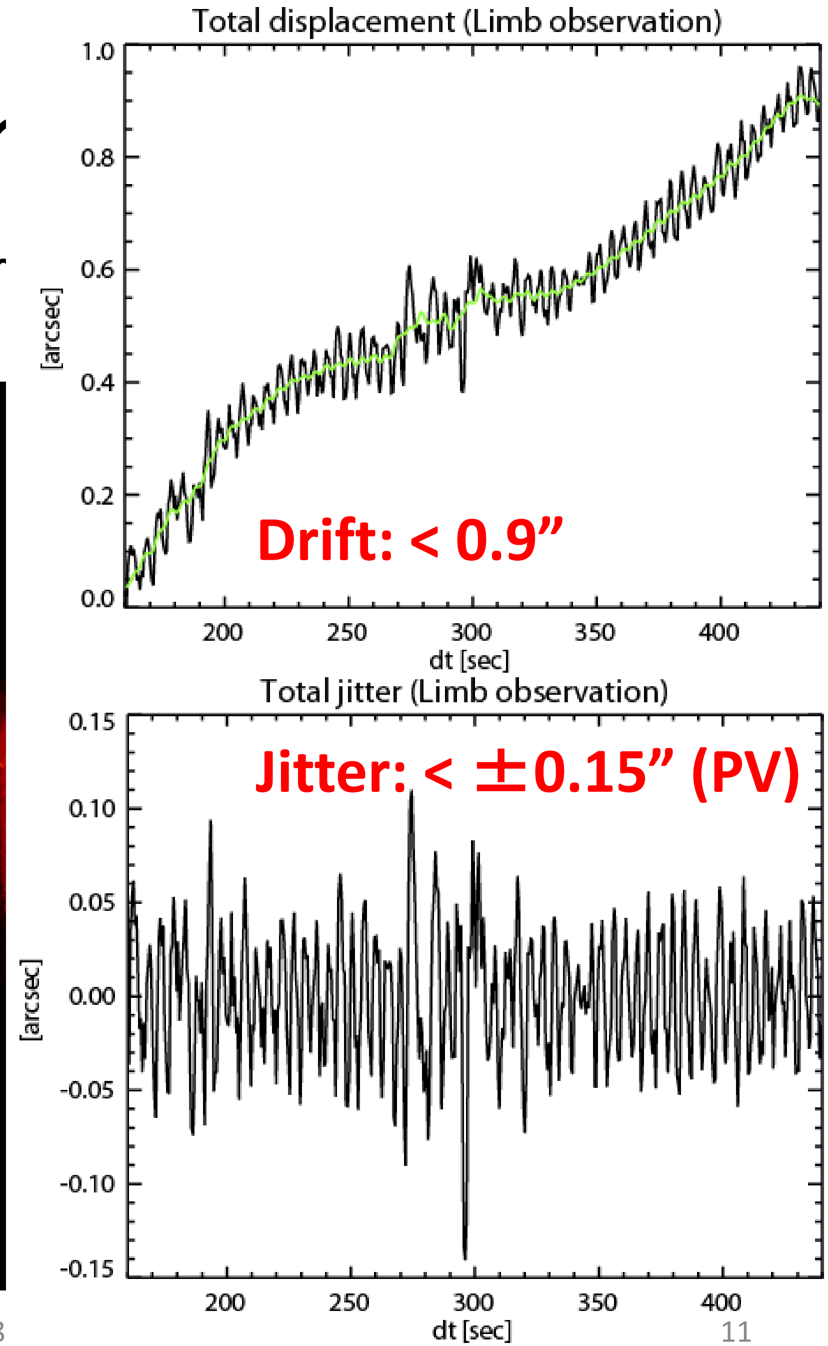


Observing pr

Peak height was

[CLASP **Slitjaw(SJ) movie**





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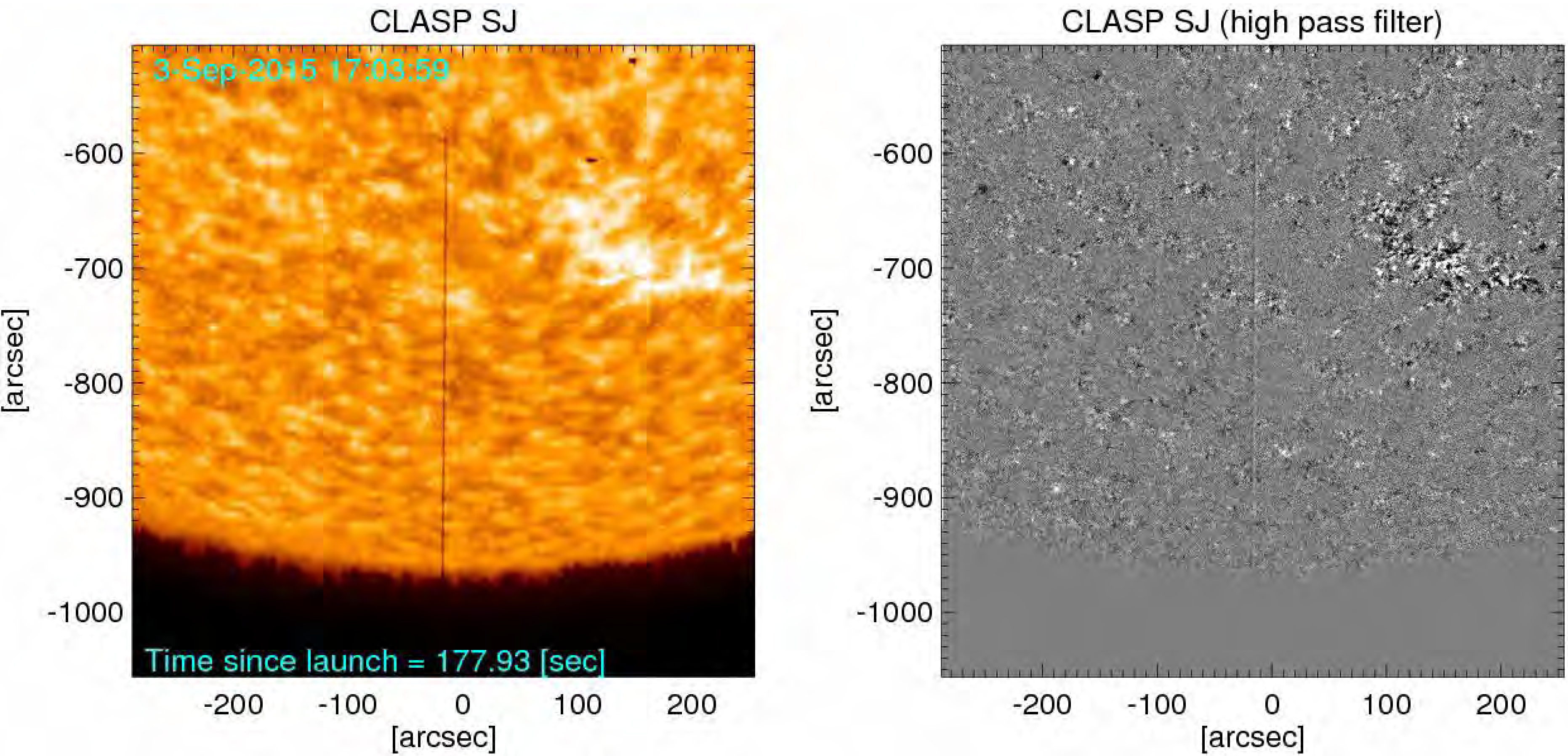
d.

CLASP/SJ images with high pass filter

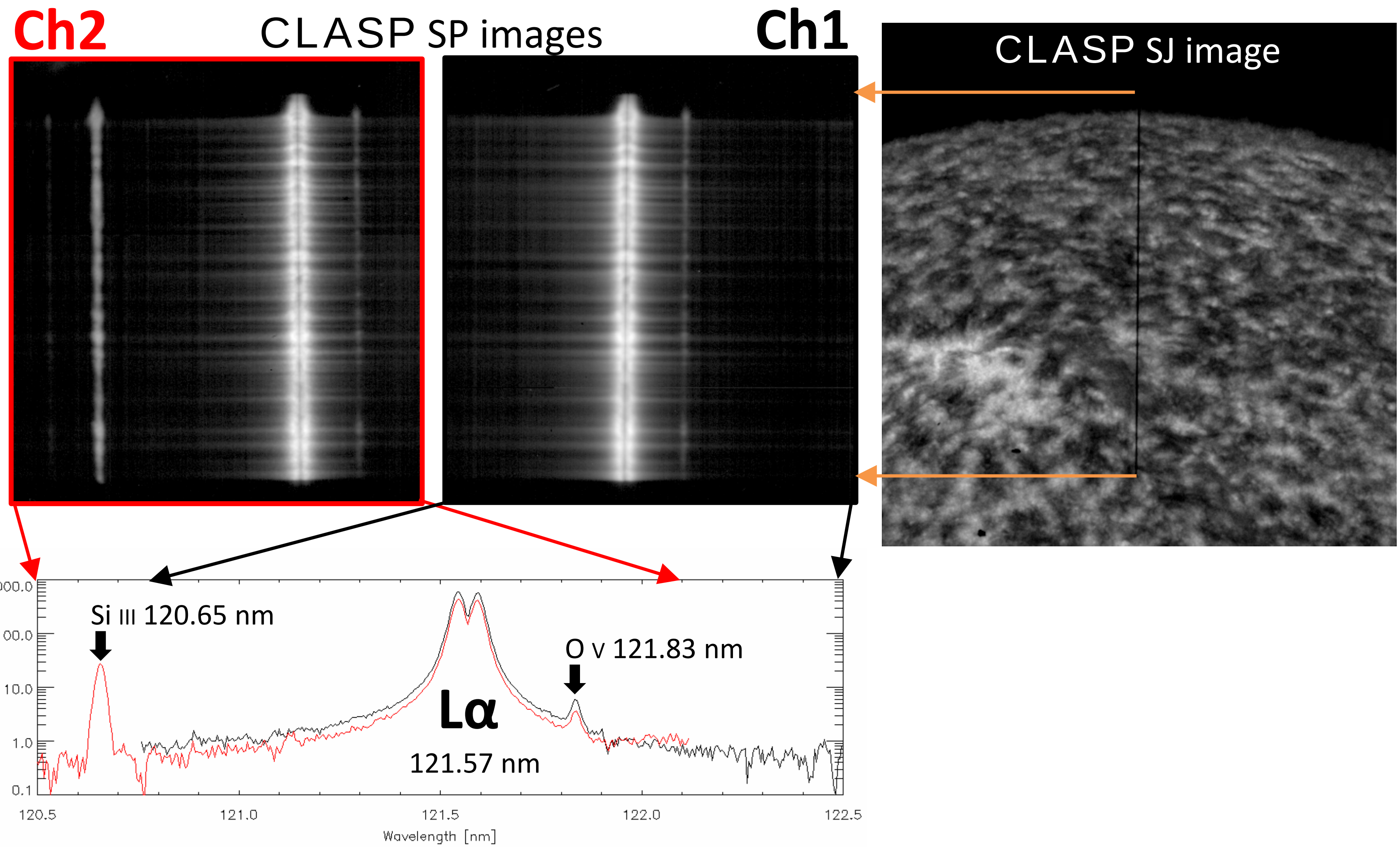


Many fast intensity fluctuations appear both in an active region and quiet Sun, after high-pass filter was applied.

"high-pass filter"

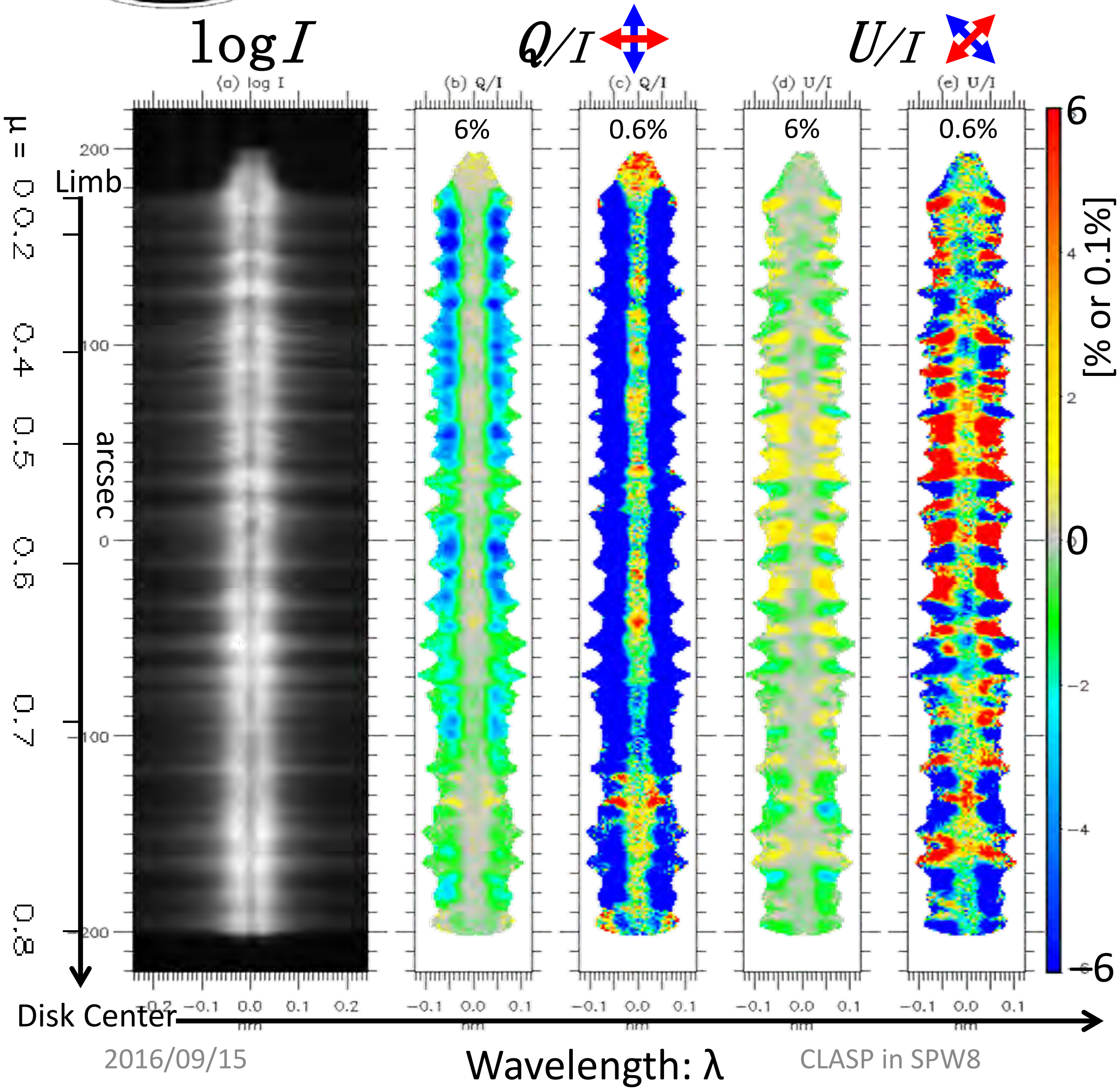
1. Subtract a running average of 30s-int. from the original images.
2. Take a running average of 4.8s-int. to remove the effect of the PMU rotation (4.8s/rot).

Lyman-α Spectrum
taken with Spectro-Polarimeter (SP)



t-averaged λ-x plot

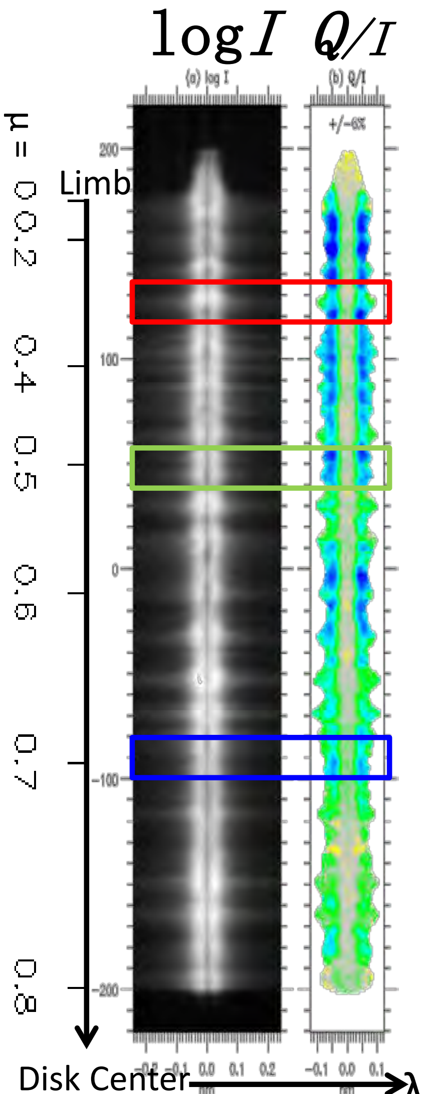
Lyman-α Polarization: Stokes-IQU



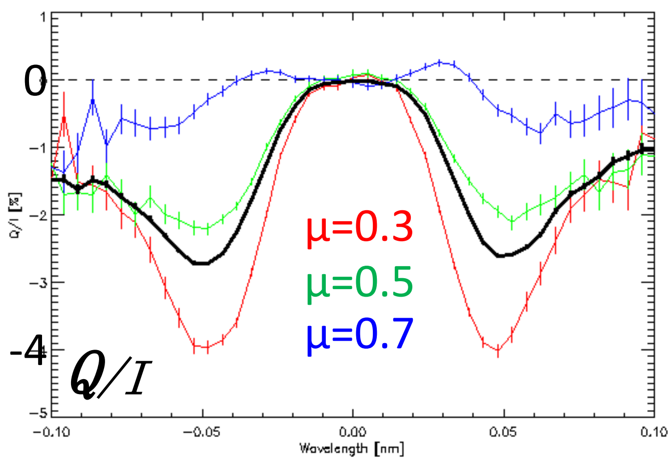
- **First detection** of Lyα pol.:
  1～6 % in the wing &
  ～0.5 % in the core.
- A clear **C-to-L variation** in the wing of *Q/I*, but **NOT** in the core.
- **Positive** *Q/I* above the limb.
- Small-scale (10”～20”) structures in *Q/I* and *U/I* as well as *I:*

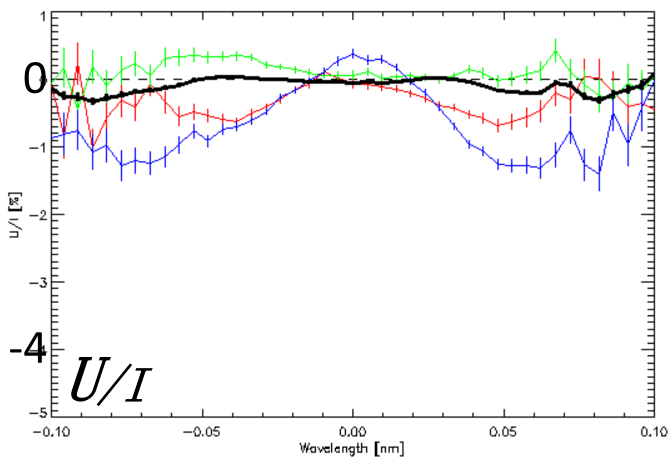
  ➔Not only local plasma conditions (*T*, *ne*, etc.) but also **local *B* distribution** may affect the polarization signals.

Stokes Profiles

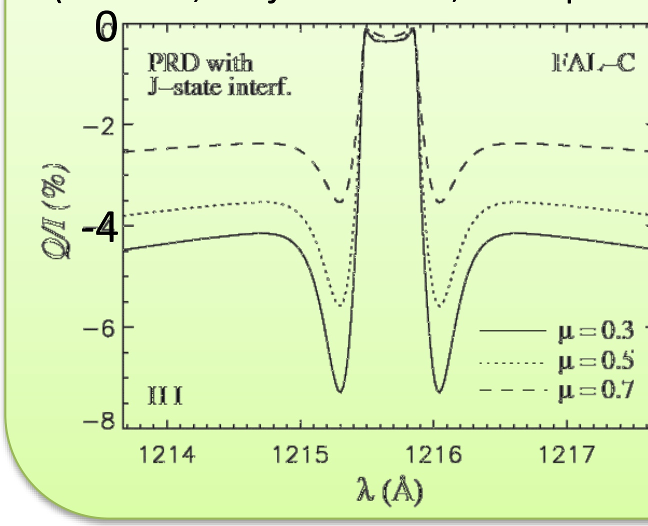


Observed Pol. Spectra





Theoretical Prediction
(Belluzzi, Trujillo Bueno, & Štěpán 2012)



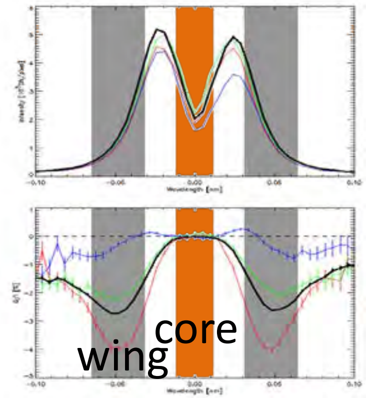
- The ***Q/I*** **profile** & **CLV in** ***Q/I*** **wing** are essentially **consistent with the theoretical prediction**.

But

- The **amplitude** & **peak separation** are slightly different with those in the FAL-C model.

➔ The CLASP observations can help us constrain the structure of the quiet solar chromosphere.

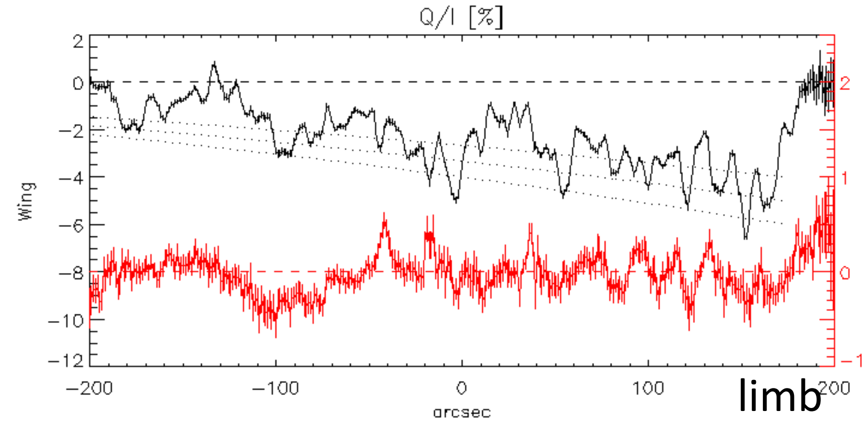
Center-to-Limb variation

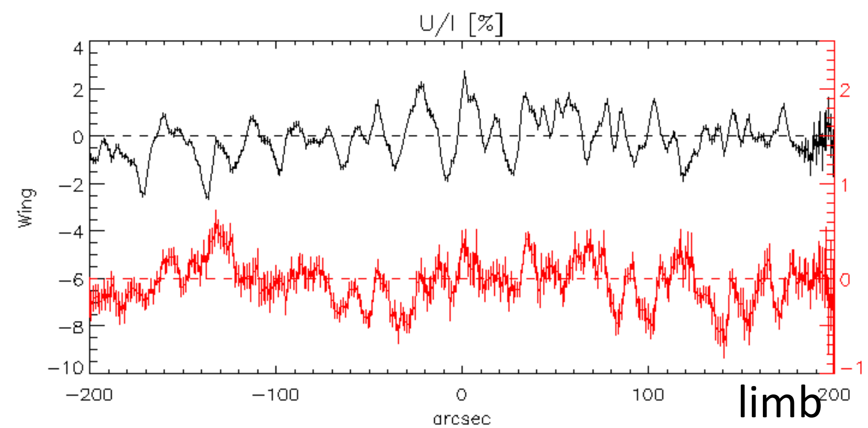


- A clear CLV in **the wing** of *Q/I*, following the **(1-μ^2)** trend (dotted lines).
- But not in **the core** of Q/I.

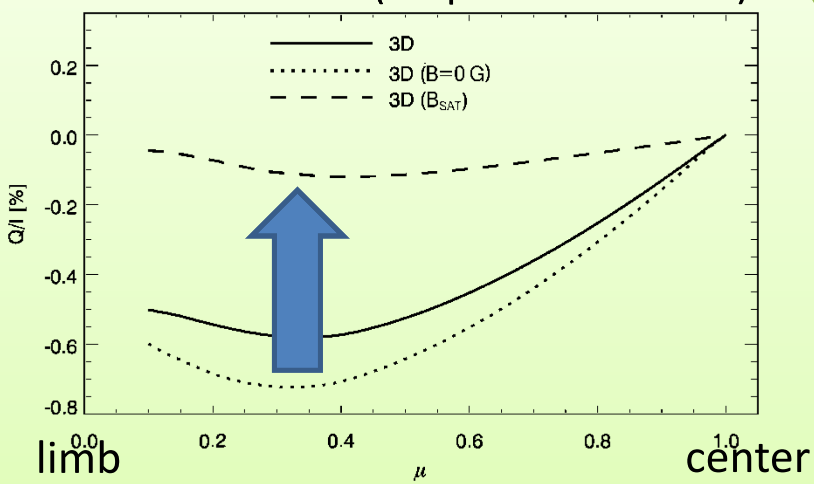
→ Chromospheric magnetic fields ***B*** **(>100G)** produce a very significant line-core depolarization by the Hanle effect.

Observed Profiles along the slit





CLV in a 3D model (Štěpán et al. 2015)



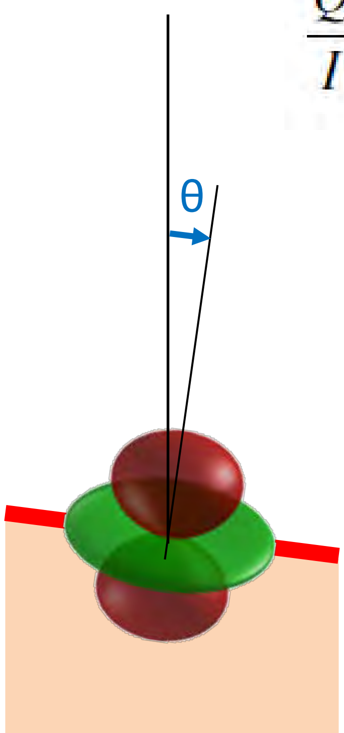
What was expected in Scattering Polarization

- In a plane-parallel atmosphere without magnetic fields, the Lyα scattering polarization can be qualitatively understood:

$$\frac{Q}{I} \approx \frac{1}{\sqrt{2}} \boxed{(1-\mu^2)} \mathrm{W}_2(j_l, j_u) \boxed{\frac{\bar{J}^2_0}{\bar{J}^0_0}}$$

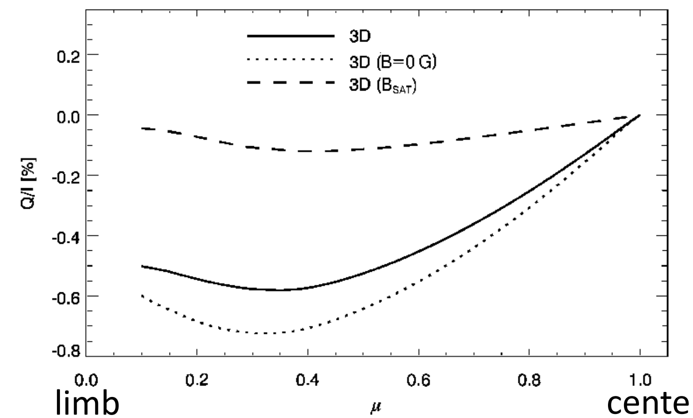
where $\mathrm{W}_2(j_l, j_u) = 1/2$ for the Lyman lines

Trujillo Bueno et al. (2001)

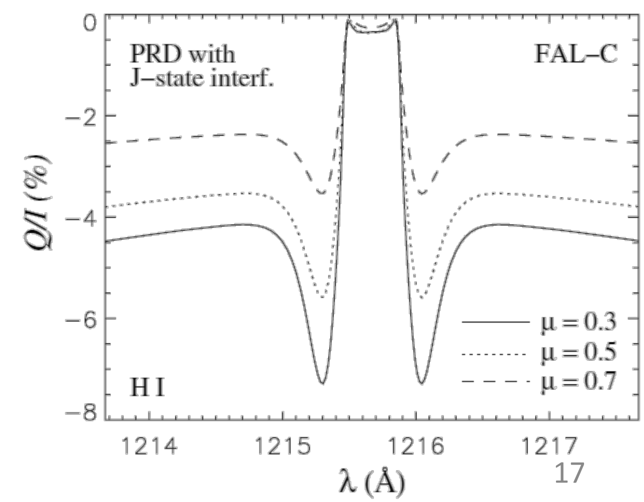


- $\mu = \cos\theta$: the angle between normal and LOS.
- J^2_0 : the anisotropy between vertical and horizontal illuminations of the atoms in the solar atmosphere.
  - Q/I < 0 in the disk, because the pumping Ly-α radiation is predominantly horizontal.
  - Q/I > 0 above the limb, because the vertical illumination dominates.

- In the core (Štěpán et al. 2015),



- In the wing (Belluzzi et al. 2012)

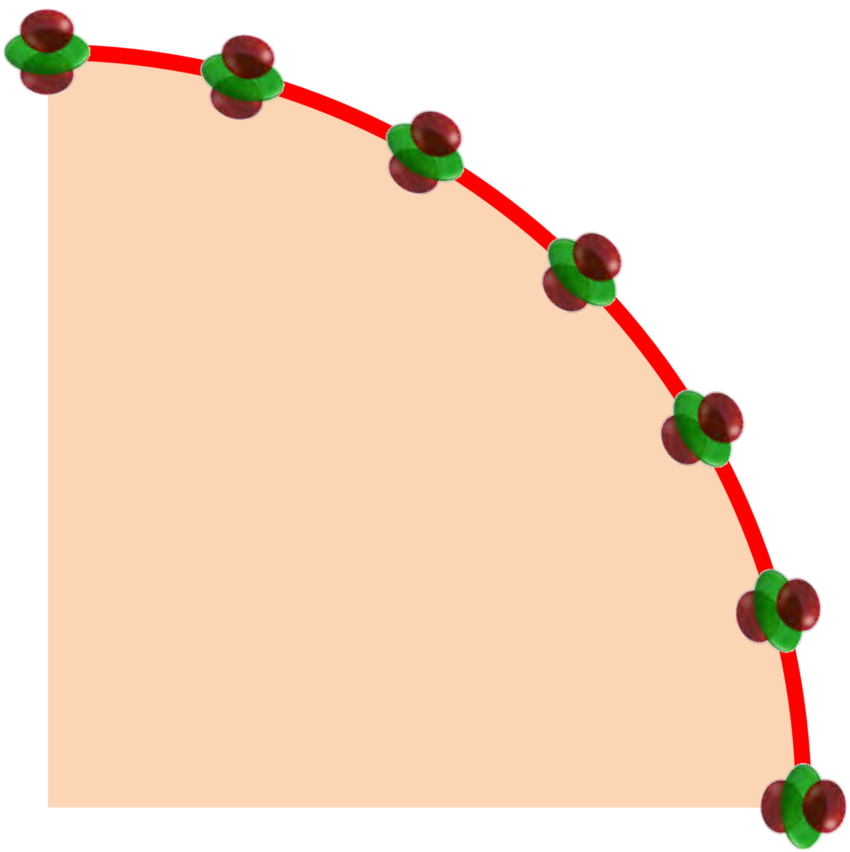


Spatial Trends

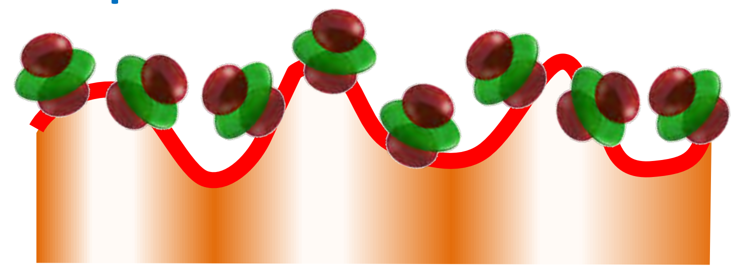
$$\frac{Q}{I} \approx \frac{1}{\sqrt{2}} \boxed{(1-\mu^2)} \mathrm{W}_2(j_l,\, j_u) \boxed{\frac{\bar{J}^2_0}{\bar{J}^0_0}}$$

where $\mathrm{W}_2(j_l,\, j_u) = 1/2$ for the Lyman lines

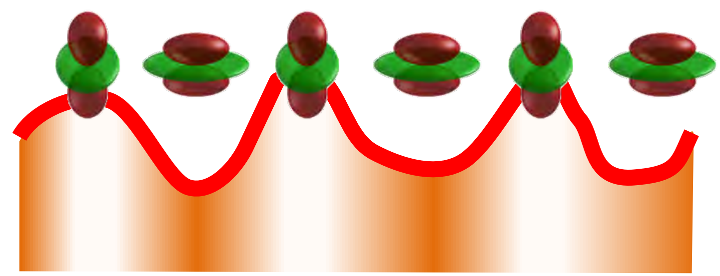
- Global trend



- Local trend
  - μ variation



  - J^2_0 variation

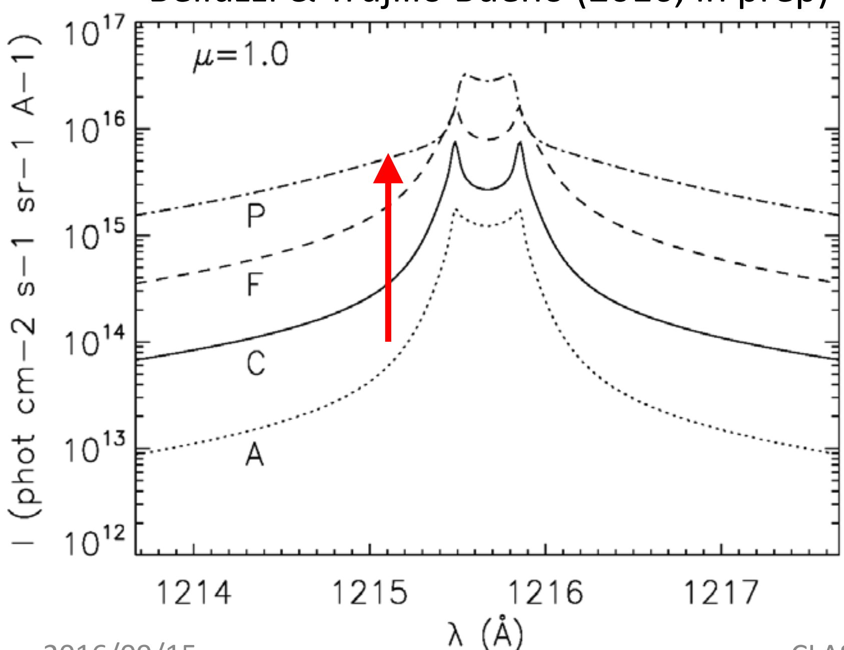


See talk by Štěpán, Trujillo Bueno et al.

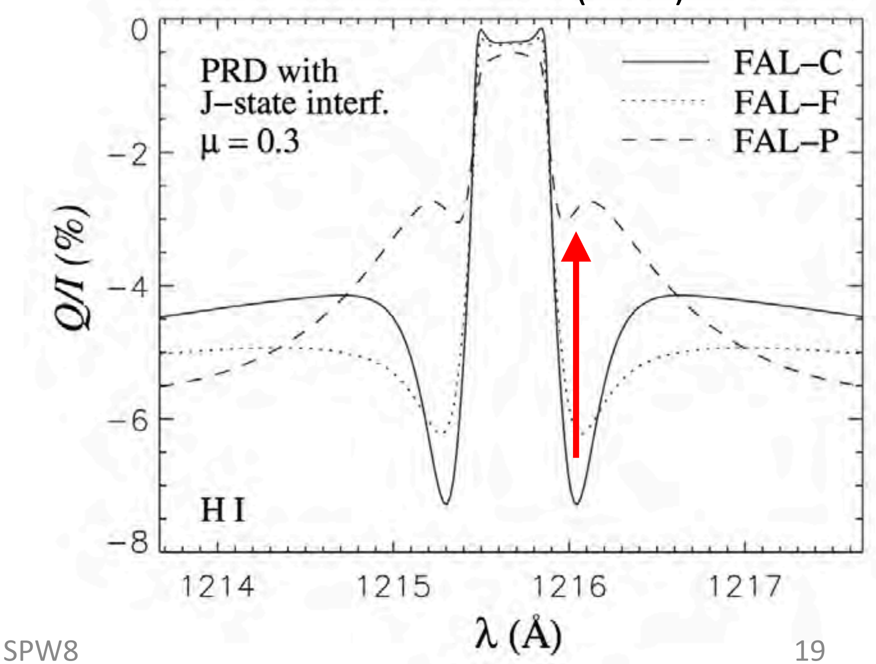
Lyα Int. vs. Linear Pol.

- In a plane-parallel atmosphere (FAL), they are anti-correlated.
  - FAL-P (plage model): Brighter ⇔ Smaller Pol. @ line wing
  - FAL-C (quiet Sun model): Fainter ⇔ Larger Pol. @ line wing

Belluzzi & Trujillo Bueno (2016, in prep)



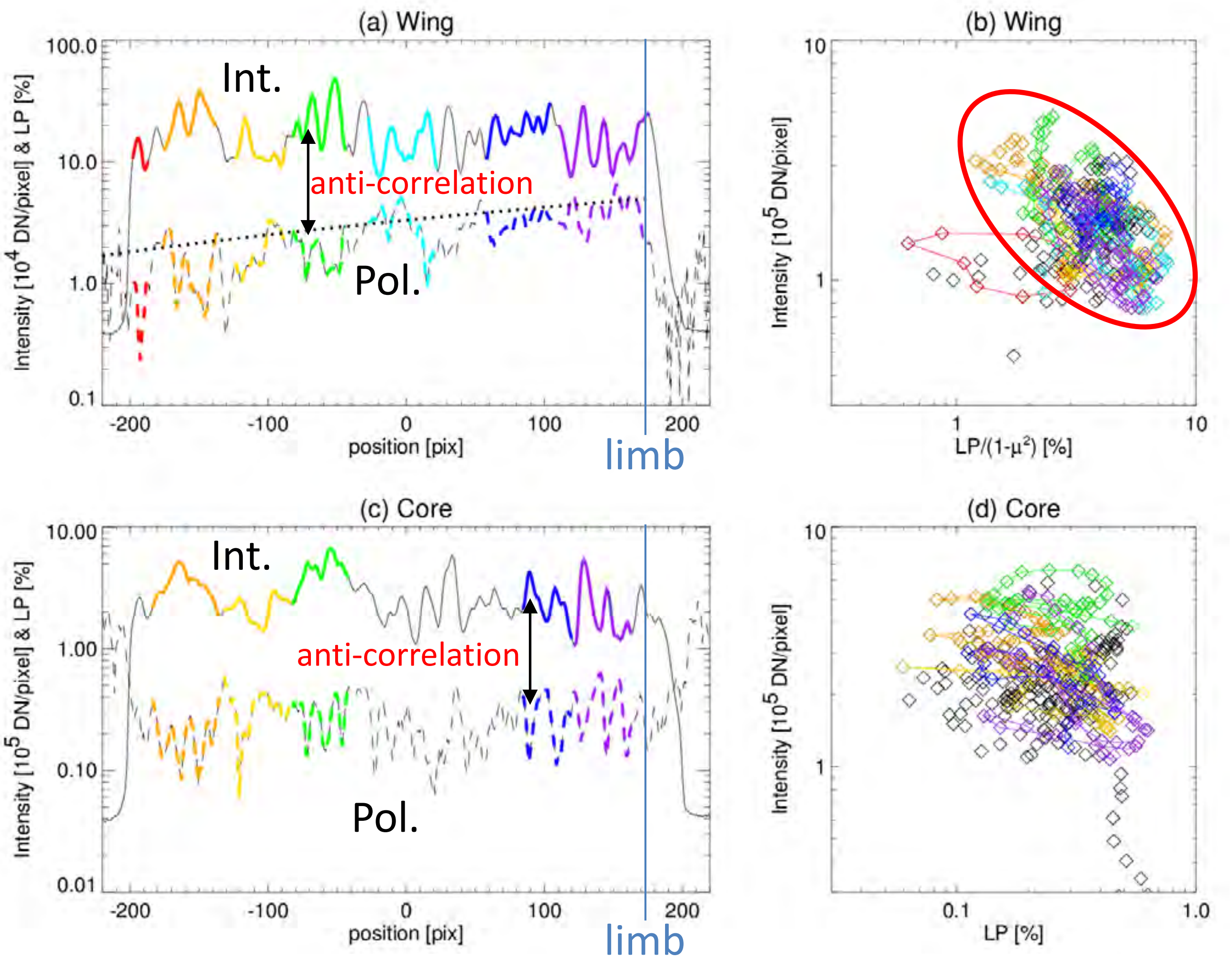
Belluzzi et al. (2012)



How about in CLASP data: Lyα Int. vs. Linear Pol.

In the line wing,
many of local variations in Pol. is **anti-correlated** with the intensity.

→ Mainly, J_0^2 variation may cause the local variation in Pol.



In the line core,
a similar anti-correlation is seen in some areas, but largely scattered.

→ Larger scatter than in the wings might be affected by magnetic fields.

Summary

- CLASP was **successfully** launched on Sep.3, 2015, and made a **perfect** Lyman-α spectro-polarimetric observation.
- **A few %** of polarization were observed in the Lyman-α wing, and **a few of 0.1 %** in the core.
- A clear **C-to-L variation** in the wing of *Q/I*, but **NOT in the core**.
- Small-scale (10”～20”) structures in *Q/I* and *U/I* as well as *I*.

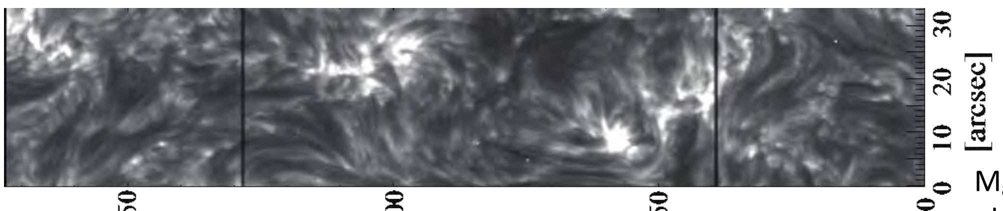
Science Papers: in prep. & in press

- **High-precision UV spectropolarimetric observations**
  - Kano et al. : Discovery of **scattering polarization** in the **Lyα line**.
  - Ishikawa,R. et al. : Scattering polarization in **Si III 120.6nm** line and indication of **Hanle effect** by comparing with Lyα.
  - Narukage et al. : **Temporal variations** of the polarization in the Lyα line.
  - Katsukawa et al. : On the possibility of scattering polarizations in the **O-V line**
  - Štěpán et al.
  - Trujillo Bueno et al.

  : Papers on interpretation by comparing with model calculations.
- **High-cadence Lyα imaging** by Slitjaw optics.
  - **Kubo et al. (2016, ApJ)** : **Fast-Propagating Intensity Disturbances**
  - Ishikawa,S. et al. : Activities at **Coronal-Loop Footpoints**
  - Suematsu et al. : Spicules.
- **Lyα spectral observation**
  - Winebarger et al. : Spectral analysis of Lyα intensity profiles
- Polarization Calibrations
  - **Giono et al. (2016, SP)** : Pre-flight polarization calibration
  - Giono et al. : In-flight polarization calibration

What's next? CLASP2

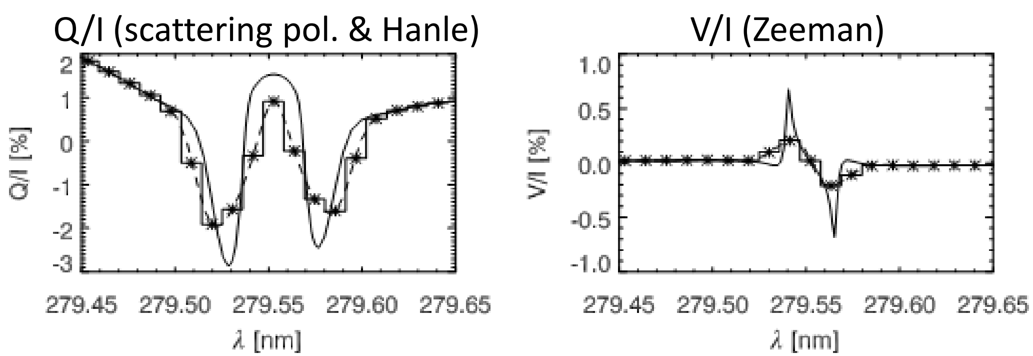
- The same optical design and structure, but for ***Mg II h & k***.



Observing target: QS and plage (if available)

Mg II h& k line core image obtained by IRIS

- And take ***Full Stokes***.



Measurement of ***circular*** as well as linear polarizations

Belluzzi & Trujillo Bueno (2012; ApJ letters).

- We will propose to fly in 2019 Spring!

Acknowledgement

The CLASP project is funded by:

- **US participation:**
  NASA Low Cost Access to Space (Award No. 12-SHP 12/2-0283).
- **Japanese participation:**
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